IN-DEPTH BLOCKING TO BOOST LATE LIFE RESERVES

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ABSTRACT

The published literature on deep flow diversion techniques was reviewed recently. No simulation studies of deep flow diversion treatments using either chemical or microbial diverting agents were identified. In contrast, significant R&D effort has been invested in developing chemical and microbial systems that might be suitable for deep applications. In view of these developments, a simulation study was undertaken, to identify scenarios in UKCS fields where deep emplacement of a mobility reducing agent would cause flow diversion recovering by-passed oil.

This study suggests that temperature triggered in-depth blocking treatments can increase ultimate recovery in heterogeneous, waterflooded formations. A variety of conceptual models of in-depth blocking agents were studied. The pre-cursor had the same viscosity as the injection water. It underwent a temperature-triggered reaction to form the blocking agent. This reduced the mobility of the water phase, either by viscosification or by adsorbing onto the rock and reducing the effective permeability. A range of reaction rates was investigated, spanning rates typical of chemical and microbial systems. Treatments were initiated when watercuts had reached approximately 90%. Incremental recoveries of a few percent of STOIIP were obtained in systems with permeability contrasts of approximately 10:1 between the high permeability thief zone and lower permeability layers. It is noted that this may represent an increase of up to 50% of the remaining reserves in mature fields.

Conditions that favour the application of in-depth blocking treatments in mature fields are:

- Regions of bypassed or unswept oil close to producers
- Situations where both producers and injectors are completed on zones with very different permeabilities, and there are continuous high permeability channels between the wells.
- Conditions where sweep is poor but the situation is unlikely to be amenable to correction by in-depth blocking are:
- Recovery of ‘stripper’ oil behind the saturation front
- By-passed regions behind sealing faults
- Channel sands situations where some producers are off-channel.

INTRODUCTION

A review of the published literature on deep flow diversion techniques found no recent simulation studies of treatments using either chemical or microbial diverting agents. In contrast, significant R&D effort has been invested in developing chemical and microbial systems that might be suitable for deep applications. For example, BP developed thermal setting gel systems in the early 1990s 1 and applied at least one system in the Kuparuk field. In view of these findings, a simulation study was undertaken, to identify scenarios in UKCS fields where deep emplacement of a mobility reducing agent would cause flow diversion recovering by-passed oil. It was recognised that incremental recoveries of a few percent of STOIIP may represent increases in remaining reserves of as much as 50% in mature fields.

RESERVOIR SCENARIOS

Simulations were performed using AEA Technology's in-house chemical flooding simulator, SCORPIO. Asymmetric, 3-D generic sector models were constructed, containing three wells, to investigate the scope for deep flow diversion agents, principally focussing on temperature triggering. These models represented a range of vertical and areal heterogeneity (Table 1). The impact of faulting and oil viscosity was also studied. Asymmetric and faulted models were chosen as being more representative of real reservoir scenarios, and potentially more challenging, than the symmetric, unfaulted models traditionally used in generic studies.

The geometry and model parameters for the base case thick layer model are shown in Figure 1. These properties are based on averaged values of the Etive and upper Rannoch in Brent Sands fields. All the waterflood and treatment cases were run for 6000 days.

DIVERTING AGENTS

The mobility reduction treatment comprised bullhead injection of a slug of pre-cursor (denoted the 'injectant') after 3000 days of waterflooding, when the sector watercut had reached approximately 90%. The injectant could adsorb onto the rock or react to form a 'product'. The injectant → product reaction rate increased exponentially with temperature and a low-temperature cut-off was applied in most cases. Two reaction rates were investigated, with timescales of 60 days and 5 days at reservoir temperature (80°C). These rates are representative of biological and chemical systems, respectively.

The product acted to reduce the mobility of fluids inside the reservoir, either by adsorbing onto the rock and reducing the permeability, or by viscosifying the aqueous phase. These two mechanisms are termed 'permeability reduction' and 'viscosification', respectively. It was assumed that the area around the injector would be thermally fractured, therefore the residual resistance factors (RRFs) associated with adsorbed product were set to 1.0 in the grid blocks in which the injector was completed. This represented limited fracture growth (up to 150 ft from the well) to compensate for any potential mobility reduction near the injector.

The product acted via permeability reduction in the base case, and the main parameters for this model are summarised in Table 2 below. Parameters that were varied during the sensitivity investigation are indicated in the final column.

BASE CASE THICK LAYER MODEL

Waterflood

The temperature distribution at the time of the chemical (or microbe) injection will control the placement of the product. The temperature and saturation distributions after 3000 days of waterflooding are illustrated in Figure 2. The temperature front lags behind the saturation front in the high permeability layer, because of the heat capacity of the rock. However, there is significant thermal conduction between the two layers, therefore the temperature front is ahead of the saturation front in the low permeability layer.

The final waterflood recovery factor was 59.4% STOIIP and the high permeability layer was well swept throughout the model. The upper regions of the low permeability layer were also well swept, by water which slumped downwards from the top layer under the influence of gravity. Unswept oil remained towards the bottom of the low permeability layer in the vicinity of the producer denoted 'Prod2', forming the target for an IOR treatment. The final pressure drop between the injector and Prod1 was 830 psi, compared to a maximum of 2800 psi; therefore surplus productivity was available.

Base case mobility reduction treatment

The base case mobility reduction treatment recovered 63.2% STOIIP, compared to 59.4% for the waterflood, corresponding to an incremental oil recovery of 3.8% STOIIP. The pressure drop between the injector and Prod1 was increased from 490 to 970 psi. The maximum pressure drop is 2800 psi, therefore the degree of mobility reduction could be increased significantly without reducing the production rates.

The oil production profiles for these cases are illustrated in Figure 3. There is a delay of approximately two years between the start of injection and the first incremental oil production from each well. The rise in injector BHP coincides with the start of incremental oil production. The blocking system is injected for one year, therefore the treatment is concluded before any effect is observed. This makes it impossible to 'tune' the system based on feedback from the reservoir and also has a detrimental impact on the discounted economics of the project.

The final placement of the product is illustrated in Figure 4. There is no product in the lower layer, because the injectant is adsorbed before the reaction is temperature-triggered in this layer. Thus the system has been successfully designed to selectively reduce the mobility in the high permeability zone.

Treatments varying amount of mobility reduction

Sensitivity cases in which the amount of permeability reduction was varied may be divided into five groups:

- Those varying the product RRF and adsorption capacity (Γ) together, keeping RRF/Γ constant. (The significance of this ratio is explained in Section 4.4.)
- Those varying the amount of product adsorption, but giving the same RRF once Γ had reached its maximum value.
- Those varying the product RRF produced for a constant adsorption capacity.
- Those for which the injectant slug size was varied.
- Those in which the injectant adsorption capacity of the high permeability layer was

varied.

Alternatively, the product was assumed to act by viscosifying the water, and a series of cases was run varying the degree of viscosification produced by the product. The product did not adsorb in these runs, therefore it was displaced through the formation by the water post-flush, and eventually produced. It is noted that this model represents a 'best case' compared, for example, to the behaviour of biopolymers in sandstone. These do adsorb at relatively low levels, without significantly increasing the RRF above unity.

The IOR and drawdown varied systematically within each series over a limited parameter range approximately centred on the base case values. The variation changed outside this range, either because the producers became BHP limited, reducing the total production rate, or because a significant amount of product was produced. Incremental recoveries ranged from negative (when the producers were severely BHP limited, i.e. the reservoir was over-treated) to 6.3% STOIIP. This upper value is not an absolute limit, but is indicative of the range of increments for this reservoir and mobility reducing system.

Discussion

The results for the base case reservoir model are illustrated in Figure 5, which shows the IOR as a function of the effective mobility (*λeff*) of the aqueous phase in the high permeability layer after treatment. The effective mobility is quoted in units of cp-1, therefore it is a measure of the relative permeability divided by the viscosity. The product slug size and the fractional rock coverage in the adsorption process are accounted for by adopting the definitions below:

$$\lambda_{eff} = \frac{1}{\mu_w} \cdot \frac{1}{\frac{1-f}{k_{rw}} + \frac{f.RRF}{k_{rw}}} \quad \text{for adsorption and permeability reduction}$$

where *f* is the fraction of the upper layer for which the permeability is reduced.

$$\lambda_{eff} = \frac{1}{\frac{(1-f^*).\mu_w}{k_{rw}} + \frac{f^*.\mu_P}{k_{rw}}} \quad \text{for a viscosifying product}$$

where *f** is the product slug size as a fraction of layer pore volume.

The untreated effective mobilities were 0.75 cp^{-1} for all the reservoir models studied.

Cases belonging to one series of simulations are indicated by coloured lines in Figure 5. In general, the IOR increases systematically with decreasing post-treatment effective mobility, i.e. with increasing severity of the treatment. Consequently, this is a useful method of characterising the results.

The exception is the series for which RRF/Γ=constant, and the case denoted A in Figure 5 is clearly anomalous, even within this sequence. The adsorption capacity of the high permeability layer was set at too low a value to 'capture' all the product in this case, therefore a significant amount was produced.

The final effective mobility is virtually constant for the other cases in the series with RRF/Γ=constant, therefore the IOR might also be expected to be very similar. In practice, the IOR increases as both Γ and the RRF decrease, i.e. as the size of the treated region increases.

It seems plausible that increasing the treated volume increases the distance over which chase water is diverted into the lower before returning to untreated zones in the upper one. If this is the correct explanation, the increase in IOR is a cross-flow phenomenon that should disappear if there is a sealing barrier between the two layers. This point will be returned to in Section 5.2.

The product gives higher IORs for a given effective mobility reduction when it acts as a viscosifier than when it acts as a permeability reducer (Figure 5). This is attributed to diversion of chase water around the viscosifying slug, as discussed above for the RRF/Γ=constant cases. The cross-flow is more effective for a viscosifying product, however, because the region of the lower layer swept by cross-flow advances as the product slug moves through the upper layer.

Sensitivity of results to oil viscosity

Waterflood and mobility reduction treatment cases were run for oil viscosities of 2.0 cp and 0.3 cp, compared to 0.8 cp for the standard model. These values approximately encompass the range found in light oil fields on the UKCS.

The waterflood recovery increases as the oil viscosity decreases and the saturation front has reached Prod2 in the low permeability layer for the lighter oil case, therefore only 'stripper oil' remains. The IOR from the treatment is only 0.3% STOIIP in this situation, suggesting that in-depth blocking is not an effective method of recovering 'stripper oil' behind the saturation front.

In contrast, there is a large unswept oil target in the low permeability layer in the heavier oil case. The mobility reduction treatment primarily increases the throughput in this layer, therefore it recovers a large amount of incremental oil (7.1% STOIIP) in this situation. This study suggests that in-depth blocking treatments are most effective in layered systems where a well might be abandoned before the saturation front has broken through in the lower mobility layers.

VARIATIONS ON THICK LAYER MODEL

Two variations on the basic thick layer model were studied: one with the effective vertical permeability increased by approximately a factor of 15 and one with no communication between the layers (Table 1).

Model with increased vertical permeability

The waterflood recovers slightly more oil than in the base case model. The additional recovery comes from improved sweep of the lower layer due to increased slumping of water from the high permeability layer above. The target oil for deep flow diversion treatments is, therefore, reduced. The base case flow diversion treatment recovers an additional 2.06% STOIIP, compared to 3.79% for the Etive-Rannoch model.

The results for these cases are illustrated in Figure 6, which shows the IOR as a function of the effective mobility (λeff) of the aqueous phase in the upper layer after treatment. The base case treatment parameters are approximately optimised for this model. Increases in the severity of the treatment (by injecting a larger slug, increasing the RRF for a given adsorption level or decreasing the adsorption capacity without a corresponding reduction in RRF) give very little increase in the IOR. These strategies either cause the producers to become BHP limited, reducing the total liquid production rate, or create more product than can be adsorbed by the high permeability layer, so that the surplus is produced.

The trends shown by these cases are similar to those for the base case model. These trends suggest that diversion of water into the lower around the treated region is a significant part of the incremental recovery mechanism.

Model with sealing barrier between layers

The waterflood recovery is reduced from 59.4% to 53.1% STOIIP by the introduction of the sealing barrier, because water can no longer slump downwards, sweeping the top of the lower layer. The base case deep flow diversion treatment recovers 62.5% STOIIP, corresponding to an incremental recovery of 9.4% STOIIP. The absolute recovery is less than that for the corresponding case in the model with high vertical permeability, but the increment is much larger, because the waterflood sweep is poorer. It is noted that a conventional water shut-off treatment would also be effective in this scenario.

The results for these cases are illustrated in Figure 7, which may be compared with Figures 5 and 6. The base case treatment parameters were close to the optimum, as for the model with increased vertical permeability. The curves for cases in which the slug size was changed and either the adsorption capacity or the RRF was changed are similar to those for the other models. In contrast, the curves for cases with RRF/Γ=constant and for the viscosifying product show significant differences.

Considering the cases for which RRF/Γ=constant: Some of the product is produced in the case labelled B (Figure 7), therefore the reduction in effective mobility is less than for the other cases in this series. Case C in this series lies almost on top of the base case, which is different to the trend shown in the original model (cf. Figure 5). A larger fraction of the upper layer is treated in case C than in the base case, although the effective mobility reductions are the same. However, there is no cross-flow of chase water into the lower layer around the treated region in this model, because of the sealing barrier, therefore the areal extent of the treated region has no influence on the IOR. These cases support the hypothesis that cross-flow causes the increase in IOR with decreasing RRF and Γ in the other models.

For cases in which the product acts as a viscosifier, the IOR for a given effective mobility reduction is similar to or less than that obtained with a permeability reducing agent. In contrast, the IOR for the viscosifying product is higher in the other models. Cross-flow is impossible in the model with the sealing barrier, therefore the mobile viscosifying product is no more effective than the stationary permeability reducer. The only IOR mechanism in this model is modification of the injection and production rates for each layer in favour of the lower layer, increasing the rate at which it is swept.

FAULTED THICK LAYER MODEL

The base case thick layer model was used, but with a fault running in the y-direction between the injector and Prod1, as illustrated in Figure 8. The fault was modelled simply by reducing the transmissibility in the y-direction across it. Two sets of simulations were performed. The fault was completely sealing in one set, whereas the transmissibility was reduced by a factor of 100, representing a slightly ‘leaky’ fault, in the other set.

Waterfloods

The recoveries for the waterfloods were 55.3% and 59.6% STOIIP, for the sealing and 'leaky' faults, respectively, compared to 59.4% for the base case. The water saturation distributions at the end of these floods are illustrated in Figure 8. The reduction in oil recovery for the sealing fault is due to poor sweep 'behind' the fault, in the top left corner of the model. The recovery for the leaky fault is virtually identical to the base case, although the final saturation distributions are different, indicating that the sweep pattern has been modified.

Mobility reduction treatments

The incremental oil recovery for the base case mobility reduction treatment in the sealing fault model is significantly lower than that for the standard thick layer model. In contrast, the IOR for the treatment in the leaky fault model is slightly higher than that for the standard model. The sweep 'behind' the sealing fault is actually worse for the treatment case than the waterflood, whereas the sweep in this region is improved by the treatment when the fault is leaky.

Most of the mobility reduction occurs around the tip of the fault in these treatments. The injectant and reaction parameters were varied to alter the region in which the mobility is reduced. Very little improvement was obtained in the sealing fault model, however, and the incremental recoveries were generally lower than those for the unfaulted model. The incremental recoveries for the model with the leaky fault were consistently larger than those for the equivalent case in the model with the sealing fault.

Discussion

None of the treatments in the sealing fault model improved the sweep of the region 'behind' the fault. The IOR comes from the lower permeability layer in the vicinity of Prod2, as in the unfaulted model. The waterflood sweeps further towards Prod2 in the lower layer in the faulted model, because water is channelled in this direction by the fault. Consequently, the unswept oil target in this region is smaller than in the unfaulted model. The mobility reduction treatment recovers all the remaining oil in this region, therefore the 'optimised' IOR reflects the size of the target.

In contrast, the treatment improves the sweep 'behind' the leaky fault in the lower layer. The upper layer is swept in this area by the waterflood, because sufficient water leaks through the fault. The lower layer sweep is improved by the treatment because the throughput is increased in this layer.

In summary, these simulations demonstrate that in-depth treatments cannot ameliorate poor sweep due to completely sealing faults, as might be expected. They can, however, improve uneven sweep caused by leaky faults, provided excess productivity is available. The degree of compartmentalisation in a faulted reservoir is often uncertain. If this was so, and an in-depth blocking treatment failed, it would be impossible to attribute the cause of the failure unambiguously to the blocking agent or an inappropriate application.

THIN LAYER MODELS

Two reservoir models were studied, as summarised in Table 1. Thermal conductivity is high, therefore the system is assumed to be in vertical equilibrium. The model in which both the vertical thicknesses and the vertical permeabilities are reduced by a factor of 10 is expected to be most closely analogous to the thick layer model, because the fraction of the low permeability layer swept by gravity slumping of water from the high permeability layer would be expected to be similar.

Model with vertical permeability reduced by factor of 10

The waterflood recovery factor was 61.5% STOIIP after 6000 days, compared to a final recovery factor of 59.4% in the analogous thick layer model.

The saturation and temperature distributions at 3000 days are illustrated in Figure 9. The temperature front is vertical, owing to conduction from the high permeability layer to the low permeability layer. This contrasts with the temperature front in the thick layer models, which is illustrated in Figure 2.

The incremental oil recovery for the base case treatment is 2.4% STOIIP, compared to 3.8% for the base case thick layer model. Incremental recoveries ranging from negative values to 3.3% STOIIP were obtained by varying the injectant, reaction and product properties. The increments were generally a factor of 1.5-2 lower than for the corresponding cases in the base case thick layer model.

The sensitivity cases are illustrated in Figure 10, which shows IOR against effective mobility after treatment. This model is analogous to the base case thick layer model, therefore Figure 10 may be compared with Figure 5. Most of the trends are similar for these reservoir models, but the incremental production from the thin layer model is generally only 50%-75% of that for the thick layer model when expressed as a fraction of STOIIP.

Both the incremental oil production and the reduction in effective mobility are lower for the thin layer model than the thick layer model. The amounts of injectant are identical when expressed as a fraction of the pore volumes. The fraction of injectant converted to product is lower in the thin layer model than in the thick layer model, however (13% compared to 21%). This is caused by the differences in the temperature distributions when the slug is injected. The temperature front has advanced further into the formation in the thin-layer model (cf. Figures 2 and 9), therefore the injectant penetrates deeper before the reaction is triggered. As the injectant is adsorbed at the rate of 30 μg/g in the high permeability layer, more is lost to the formation in this model. The product is equally effective in the two reservoir models, but the injectant to product conversion is less efficient in the thin-layer model.

Model with same vertical permeability as thick layer system

The waterflood final recovery factor was 62.3% STOIIP, which is similar to that for the alternative thin layer system. The base case mobility modifier treatment recovers an additional 1.9% STOIIP. This is slightly less than that for the thin layer system with lower vertical permeability, because increased gravity slumping improves the efficiency of the waterflood.

Cases varying injectant and reaction parameters

The results from cases varying injectant and reaction parameters for both the thick layer model and the thin layer model are discussed in this section.

The base case reaction model contained two features designed to minimise mobility reduction in the low permeability layer:

- The increased injectant adsorption in the lower layer compared to the upper layer.
- The low-temperature reaction cut-off.

Cases for which the reaction parameters were constant but the adsorption of the injectant in the low permeability layer was varied gave very similar incremental oil recoveries. These cases demonstrate that preferential adsorption of the reactant in the low permeability layer is not a pre-requisite for successful treatments.

Figure 11 illustrates the IOR against effective mobility after treatment for series of cases for which the low temperature cut-off of the reaction has been varied, in both the thick layer and thin layer models. The low temperature reaction cut-off has a significant impact on the effectiveness of the treatment in this model, which assumes that thermal fractures extend only to a distance of 150 ft from the injector. It is critical for the rapidly reacting system, but less important for the slower one, as might be expected. The timescales of 60 days and 5 days at reservoir temperature (80°C) are typical of biological and chemical systems, respectively. These cases suggest, therefore, that the injectant and reaction properties are less critical for a successful biological system than a successful chemical one in reservoirs with limited thermal fracturing.

The adsorption capacity of the rock for the product was not varied in conjunction with the low temperature reaction cut-off. A 'worst case' scenario might be envisaged in which the product adsorption capacity was very high and the reaction was fairly rapid even at the injection temperature (e.g. 10°C). This combination of properties would result in a localised build-up of product in the vicinity of the injector. If the injector was thermally fractured (as most UKCS injectors are), then the fractures might grow sufficiently to compensate fully for the loss in injectivity, rendering the treatment ineffective.

CHANNEL SANDS MODELS

Single high permeability channel

The static reservoir properties for this model were identical to those for the basic thick layer model. The sector was divided into a high permeability channel (kh = 5000 mD, kv = 500 mD) and a low permeability region (kh = 100 mD, kv = 1 mD) as shown in Figure 12. The channel was confined to the right most edge of the model and comprised 40% of the pore volume (Figure 12). The well locations and constraints were identical to those for the thick layer cases. Consequently, the injector and producer 'Prod2' were completed in the channel at opposite corners of the model, whilst 'Prod1' was located in the low permeability region.

The base case model of the mobility reducing agent was identical to that for the thick layer model (Table 1), except that the pre-cursor adsorption capacity of the high permeability channel was set at 30 μg/g and that for the low permeability region was 300 μg/g.

Waterflood

The saturation and temperature distributions in the waterflood at 3000 days are illustrated in Figure 13. The water breaks through into well Prod2 after about 1000 days and Prod1 after 1500 days. Well Prod1 is affected by the low permeability and operates at close to its limiting BHP for all of the simulation.

There is no benefit in shutting well Prod2, because this reduces the amount of water injected and limits the penetration of water into the low permeability region. The oil production at 6000 days is 62% of STOIIP, comprising 100% of the recoverable oil in the channel and 71% of the recoverable oil in the low permeability region. This leaves 29 % of the recoverable oil in the low permeability region as a target for the IOR treatment.

Mobility reduction treatments

The base case treatment has virtually no effect, because most of the injectant is adsorbed in the cooled region of the high permeability channel before reaching the 50°C reaction threshold near Prod2 in the channel.

Removing the low temperature reaction threshold gave an incremental oil recovery of 0.7% of STOIIP, produced from well Prod1. The mobility reducing agent is confined to the region near the injection well in this case, causing some extra water to enter the low permeability region. The incremental oil is recovered from the top left-hand corner of the model.

The channel model differs fundamentally from the layered models because each well is completed in one facies only. Consequently, it is not possible to increase the rate of sweep of the low permeability region directly by changing the injection profile. The incremental recovery mechanism is modification of the streamtubes, diverting them into the low permeability region and increasing its rate of sweep after the high permeability channel has been treated. This diversion is similar to the cross-flow of chase water around the treated zone in the layered model, but in the areal, rather than vertical, plane.

Intersecting high permeability channels

The second channel model consists of two high permeability channels (kh = 5000 mD, kv = 500 mD) and a low permeability region (kh = 100 mD, kv = 1 mD), as shown in Figure 12. The first channel comprises 20% of the pore volume. The other channel intersects this at 90 degrees and comprises 10% of the pore volume. There is a small region where the channels are overlain, and there is assumed to be good vertical communication between them.

Waterflood

The water flood recovers 51% STOIIP at 6000 days, which is significantly lower than the waterflood recovery in the first channel model. The saturation and temperature distributions at 3000 days are shown in Figure 14, which may be compared with Figure 12 for model 1. The final sweep is poorer in all layers, because the additional high permeability channel connects the second producer directly to the injector. The water breaks through into well Prod1 after 600 days, compared to 1500 days for model 1 showing that water cross-flows readily from one high permeability channel to the other.

Mobility reduction treatments

The base case treatment recovers an additional 7.2% STOIIP. Most of injectant was adsorbed before being heated to the minimum reaction temperature. The product was generated close to the production wells in each high permeability channel, owing to the position of the temperature front at the time of treatment (Figure 13).

Removing the low temperature reaction cut-off increases the IOR to 10.2% STOIIP and reducing the injection temperature gives a further increase to 12.4% STOIIP. The high permeability channels are treated along most of their length in this case, therefore most of the areas by-passed in the waterflood are now swept.

Sensitivity cases were run to investigate any differences in efficiency between a large volume treatment of a slowly reacting substance (e.g. a microbial product) and a smaller volume treatment of a fast reacting product (e.g. a chemical). No low temperature cut-off was applied, therefore the chemical reaction occurred in the vicinity of the injector. Very little injectant travelled as far as the intersection with the second high permeability channel for the rapidly reacting system, leaving this channel effectively untreated. Consequently, the incremental oil production was smaller than for the slowly reacting system. This demonstrates that it is desirable to treat all the high permeability channels.

In cases for which no low temperature reaction cut-off was applied, and there is limited thermal fracturing, the treatment can reduce the permeability in the upper high permeability channel around the injector, modifying the inflow profile in favour of the lower permeability region. This is the same as the primary IOR mechanism in the thick layer model. It is noted, however, that any thermal fractures might grow, to compensate for the reduction in injectivity, reducing the effectiveness of the treatment near the injector.

In cases where a low temperature reaction cut-off was applied, the mobility reduction occurred in the vicinity of the producers and the IOR was reduced by 30-50%. The fast reacting system was significantly less effective in this application than the slower reacting one.

CONCLUSIONS

1. The results for each reservoir scenario are summarised in Figure 15. The ranges quoted are for in-depth blocking treatments that are approximately optimised, in scenarios for which an optimum was discovered. It is generally possible to over-treat the formation and reduce the total oil production if the properties of the diverting agent are unsuitable.
2. Although the incremental recoveries appear modest when expressed as a percentage of STOIIP, it is noted that they could represent increases of up to 50% in remaining reserves, with a potentially significant impact on late-field life.
3. The temperature and saturation distributions in waterflooded thick layer systems promote reaction of the injectant in the thief zone, generating the mobility reducing product selectively in this layer, without significant reaction in the lower permeability region.
4. There are two incremental oil recovery (IOR) mechanisms arising from this selective mobility reduction, assuming the injectors and producers are completed in both layers:
5. Modification of the injection and offtake rates to increase the throughput in the lower permeability zone and reduce it in the high permeability streak, in cases where the wells are rate limited.
6. Diversion of chase water around the treated region in the thief zone by cross-flow into the lower permeability region, assuming there is communication between the layers. This improves the sweep in the top of the lower permeability zone adjacent to the treated region.
7. For a given total reduction in effective mobility in the thief zone, a mobility reducing agent that acts as a viscosifier is more efficient than one that acts as a permeability

reducer. This is attributed to diversion of chase water around the viscosifying slug. The cross-flow is more effective for a viscosifying product because the region of the lower permeability layer swept by cross-flow advances as the product slug moves through the high permeability streak. This conclusion does not apply when cross-flow is prevented, for example by a sealing barrier between the layers.

8. Conditions which favour the application of in-depth blocking treatments in mature fields are:
   - Regions of bypassed or unswept oil close to producers
   - Situations where both producers and injectors are completed on zones with very different permeabilities, and there are continuous high permeability channels between the wells.
9. Conditions where sweep is poor but the situation is unlikely to be amenable to correction by in-depth blocking are:
   - Recovery of 'stripper' oil behind the saturation front
   - By-passed regions behind sealing faults
   - Channel sands situations where some producers are off-channel.

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Table 1: Summary of reservoir scenarios investigated	
Scenario name	**Description**
Base case thick layer model	Typical of Etive and upper Rannoch in Brent Sands fields, illustrated in Figure 1.
Thick layer model with increased k_v	Similar to base case, with k_v increased by factor of approximately 15 throughout.
Thick layer model with sealing barrier	Similar to base case, with sealing barrier between layers
Faulted thick layer model. Variants: totally sealing or partially transmitting ('leaky') fault	As base case, with fault represented as transmissibility barrier in y-direction extending across 2/3 of model. Illustrated in Figure 8.
Thin layer model. Variants: k_v as in base case or reduced by factor of 10	As base case, but with all y-dimensions and well rates reduced by factor of 10, representing central 2 layers of multi-layered system.
Channel sands model with one high-k channel	Static parameters as base case. High-k channel connecting Inj and Prod2, illustrated in Figure 12.
Channel sands model with two high-k channels	As single channel model but with channel connecting Inj and Prod2 in top half of model. Intersecting channel to Prod1 in lower half. Illustrated in Figure 12.

Table 2: Summary of mobility reducer model parameters		
Parameter	**Value**	**Varied?**
Injectant BHT	10°C (50°F) (as waterflood)	N
Injectant viscosity	0.4 cp (as water)	N
Product viscosity	0.4 cp for permeability reducer	N
	5.12 for viscosifier	Y
Injectant adsorption level in high-k layer	30 μg/g	N
Injectant adsorption level in low-k layer	300 μg/g	Y
Product adsorption level in both layers	20 μg/g for permeability reducer	Y
	0 μg/g for viscosifier	N
Residual resistance factor for adsorbed injectant	1.0 (both phases)	N
Residual resistance factor for adsorbed product	20.0 (both phases) for perm reducer	Y
	N/A for viscosifier	N
Adsorption rates	Instantaneous	N
Injectant → product reaction half-life	60 days at 80°C	Y
Temperature dependence of reaction rate	Exponential with cut-off at 50°C	Y
Reaction stoichiometric coefficient	1.0	Y
Time at which injection starts	3000 days	N
Duration of injection	365 days	Y
Injection rate	Full voidage replacement	N

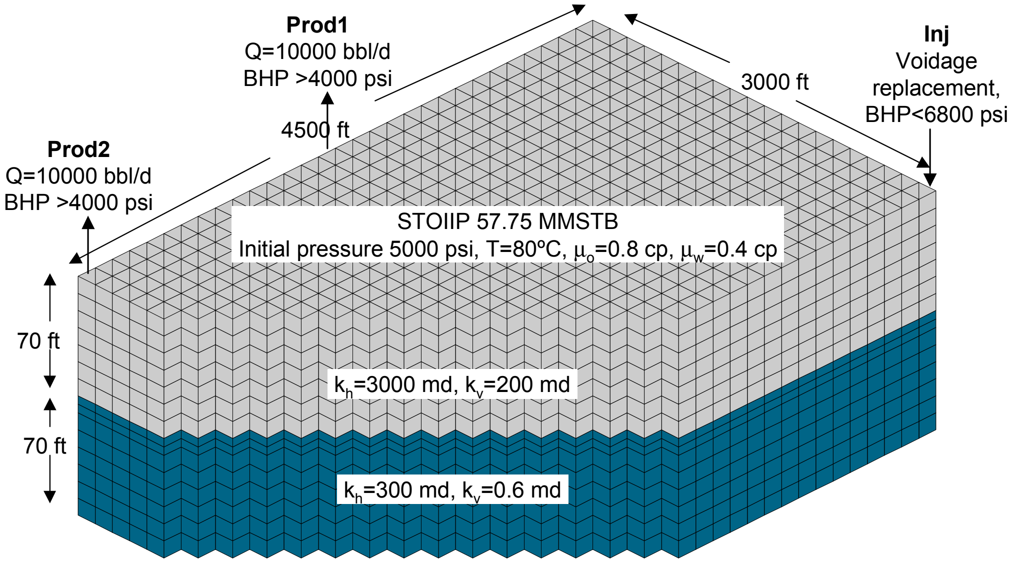

Figure 1: Schematic of base case thick layer 'Etive-Rannoch' model

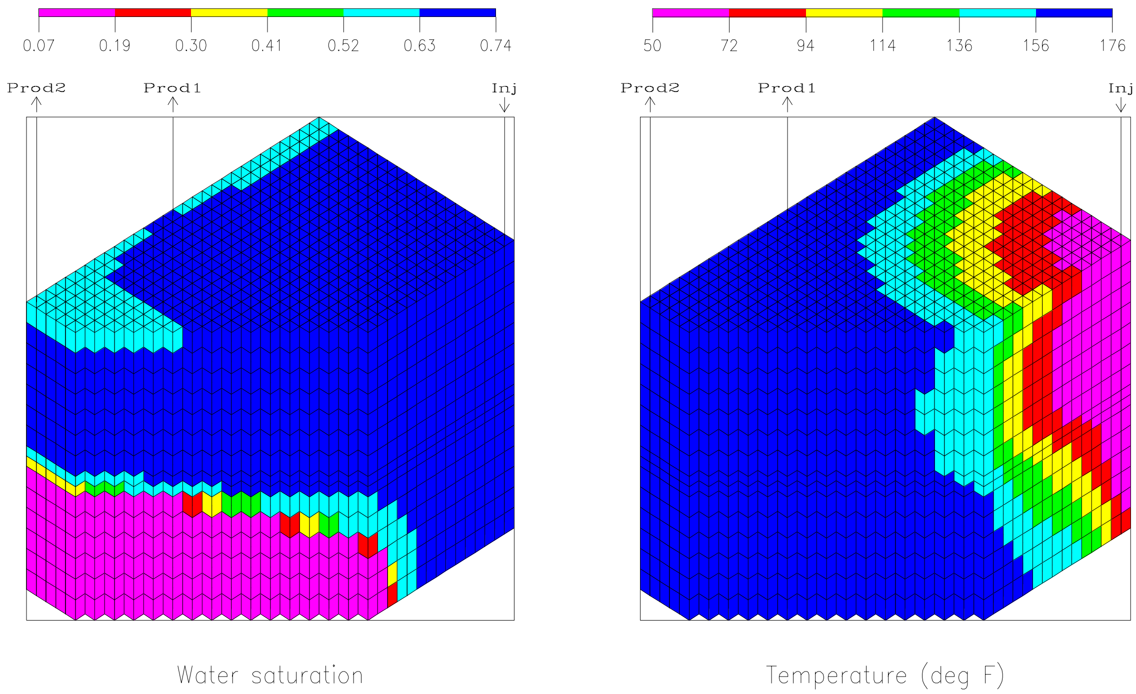

Figure 2: Temperature and water distributions at start of treatment (3000 days) in base case thick layer model

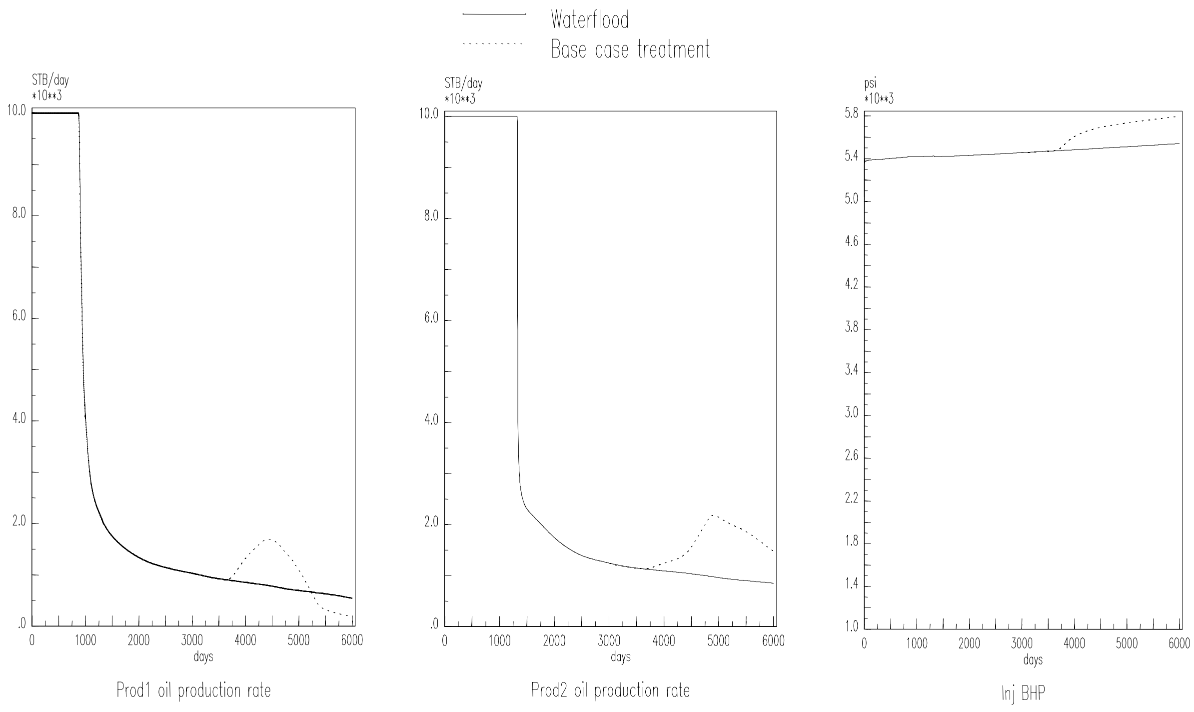

Figure 3: Oil production profiles and injector BHP for thick layer model waterflood and base case treatment

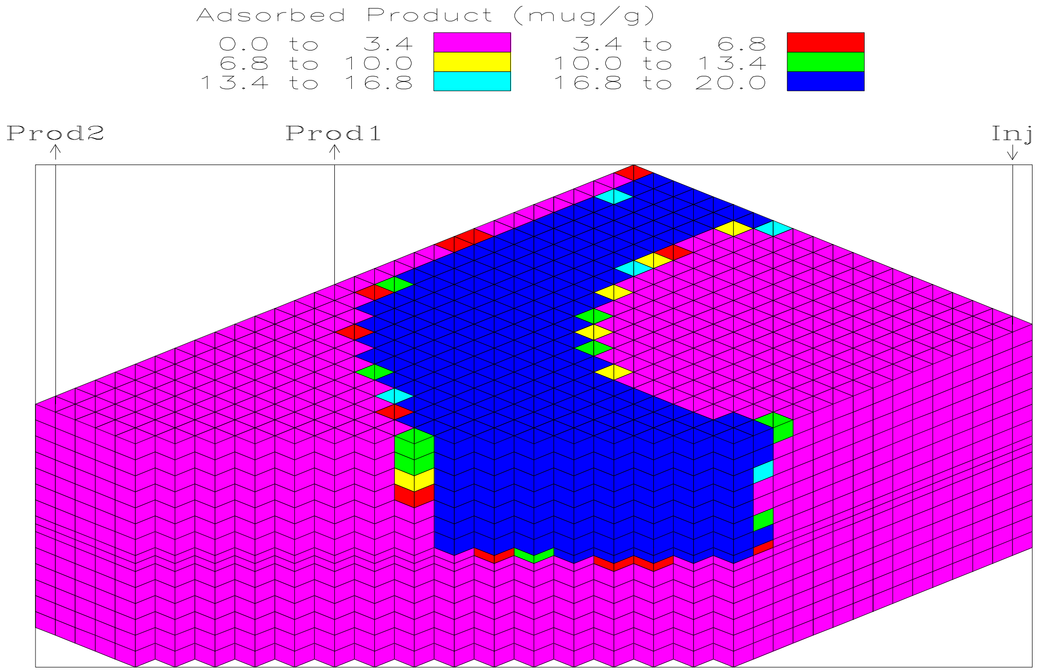

Figure 4: Final placement of mobility reducing agent in thick layer model base case treatment

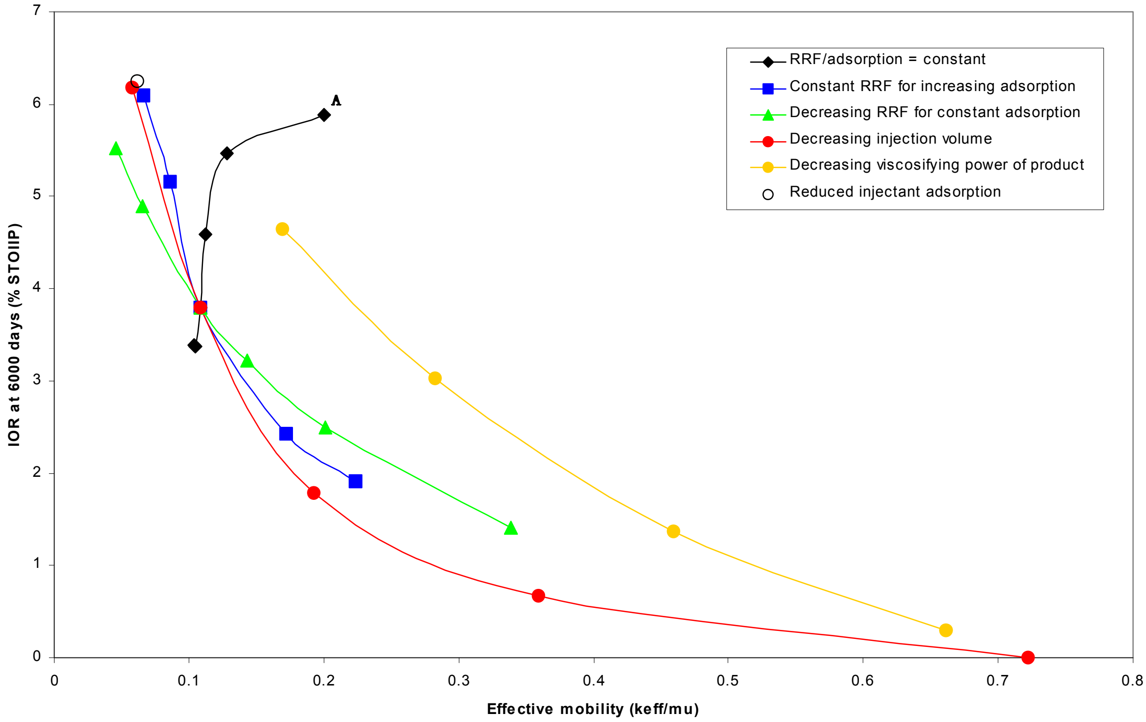

Figure 5: IOR vs. final effective mobility for base case thick layer model treatments

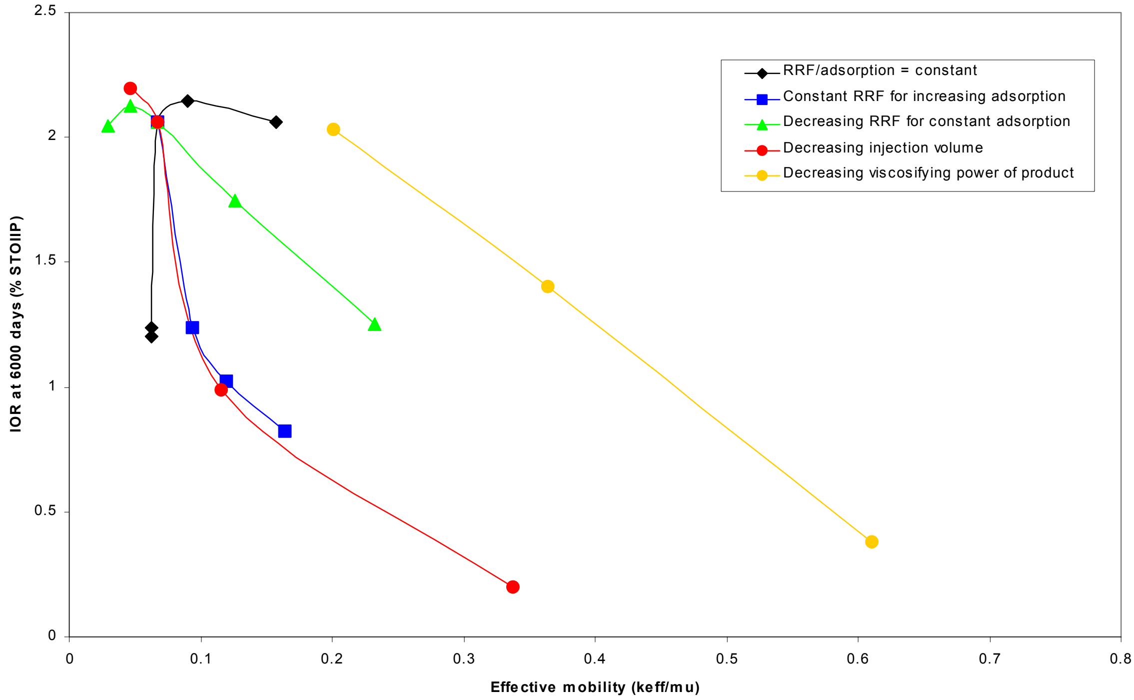

Figure 6: IOR vs. final effective mobility for treatments in thick layer model with increased vertical permeability

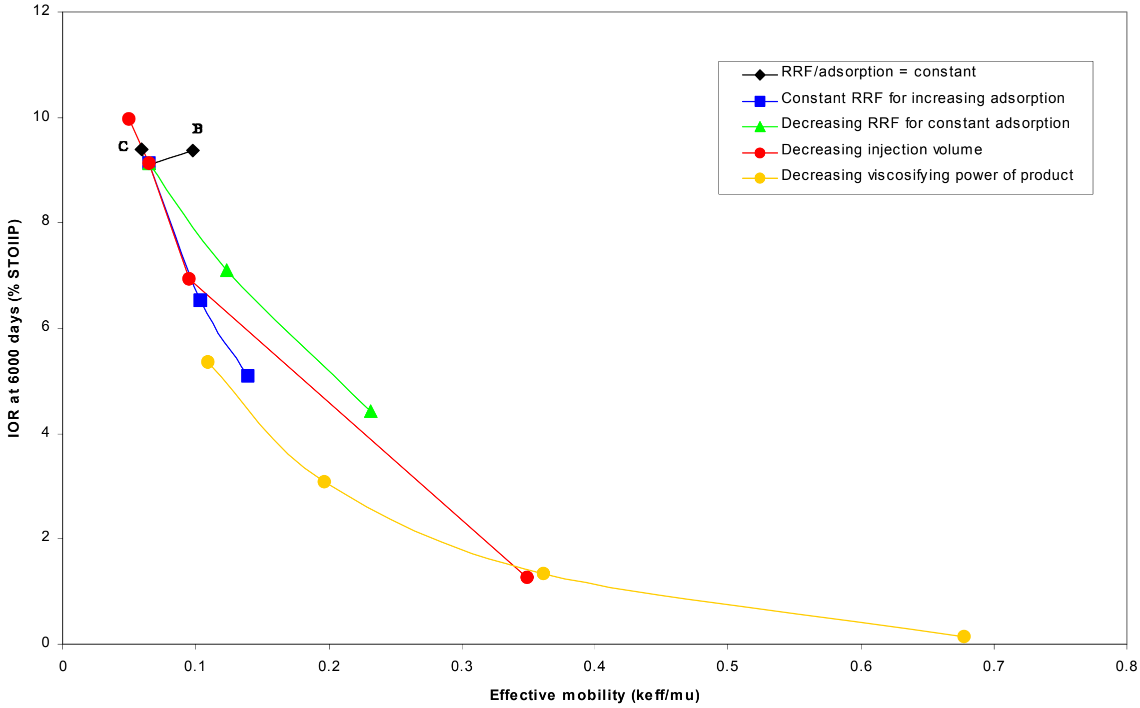

Figure 7: IOR vs. final effective mobility for treatments in thick layer model with sealing barrier between layers

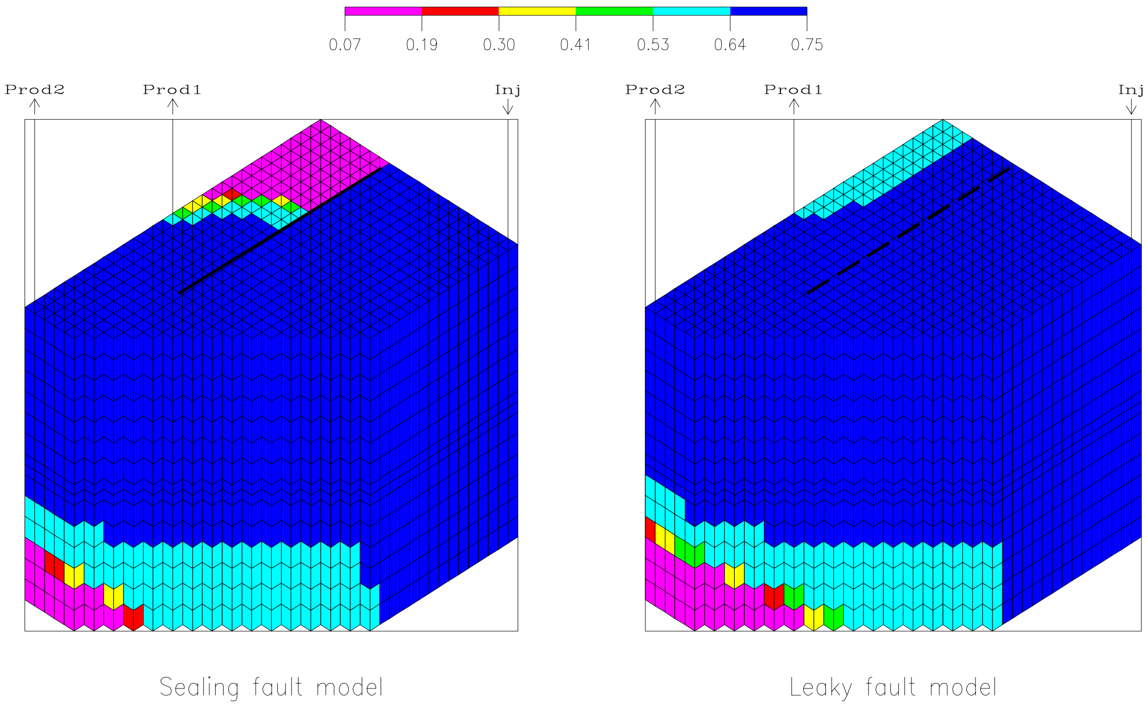

Figure 8: Final water saturations in thick layered models with sealing and leaky faults

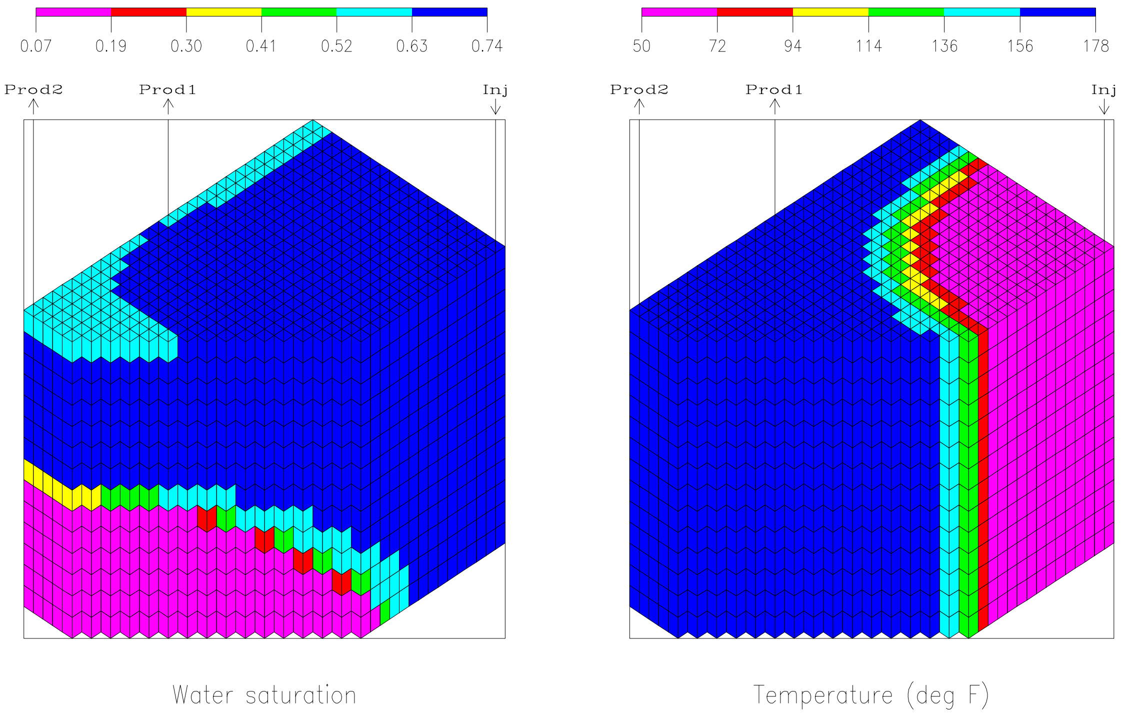

Figure 9: Water and temperature distribution at start of treatment (3000 days) in thin layer model

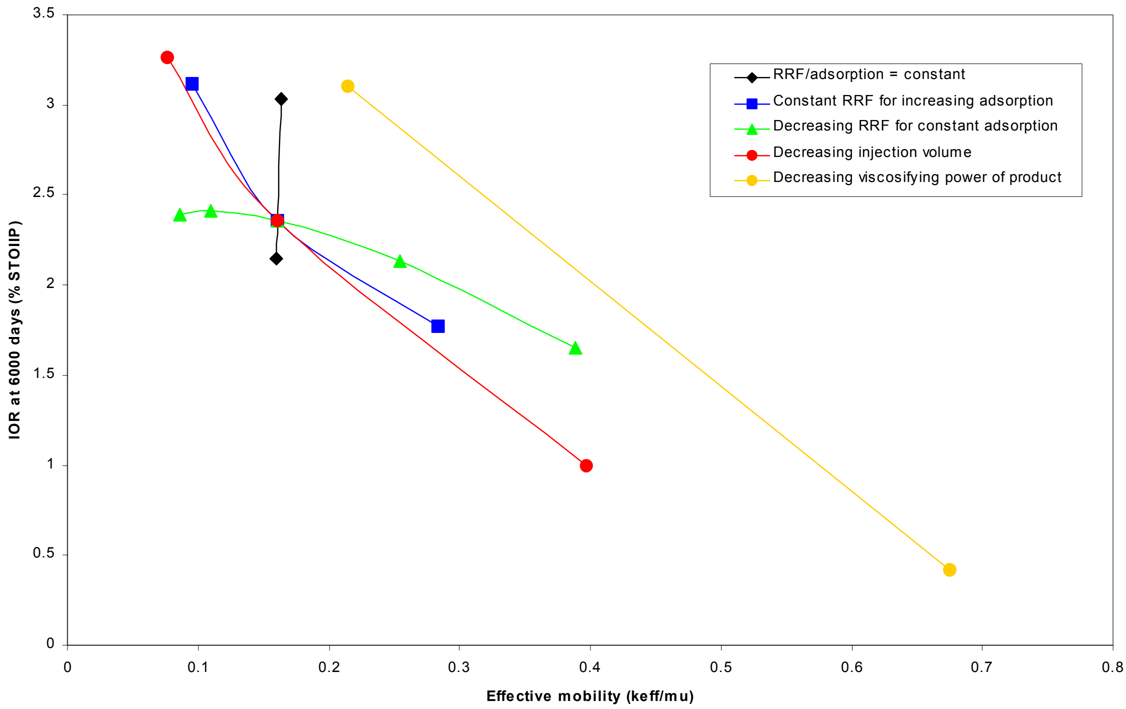

Figure 10: IOR vs. final effective mobility for treatments in thin layer model

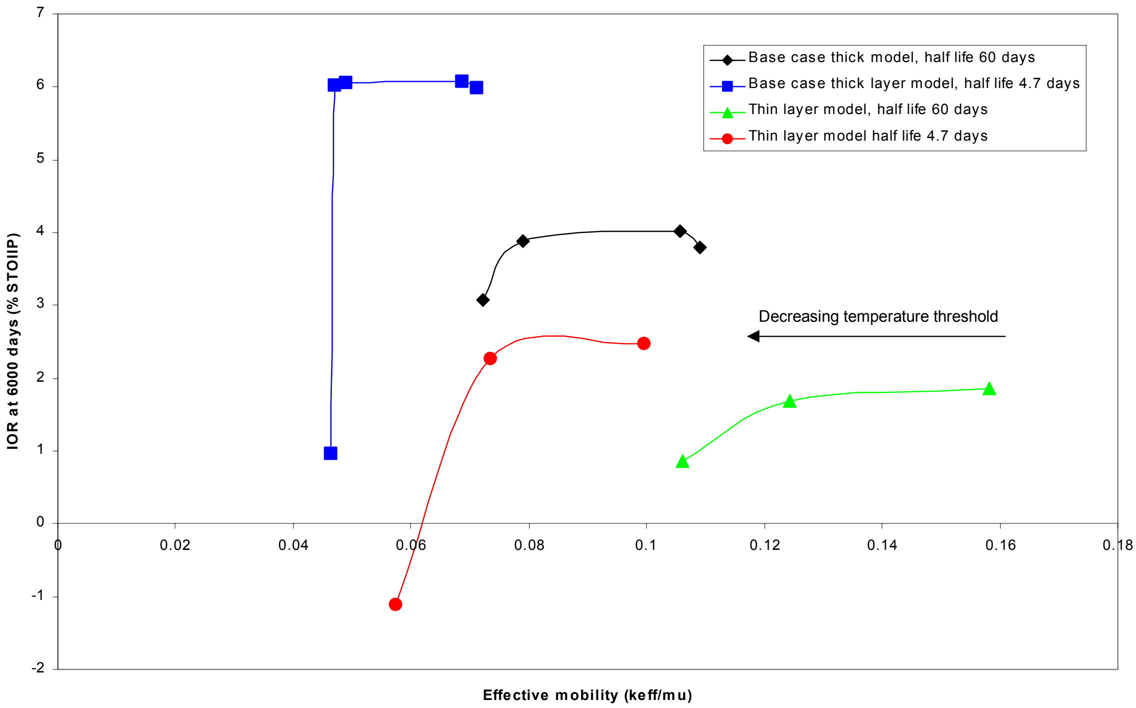

Figure 11: IOR vs. final effective mobility for treatments varying reaction temperature threshold

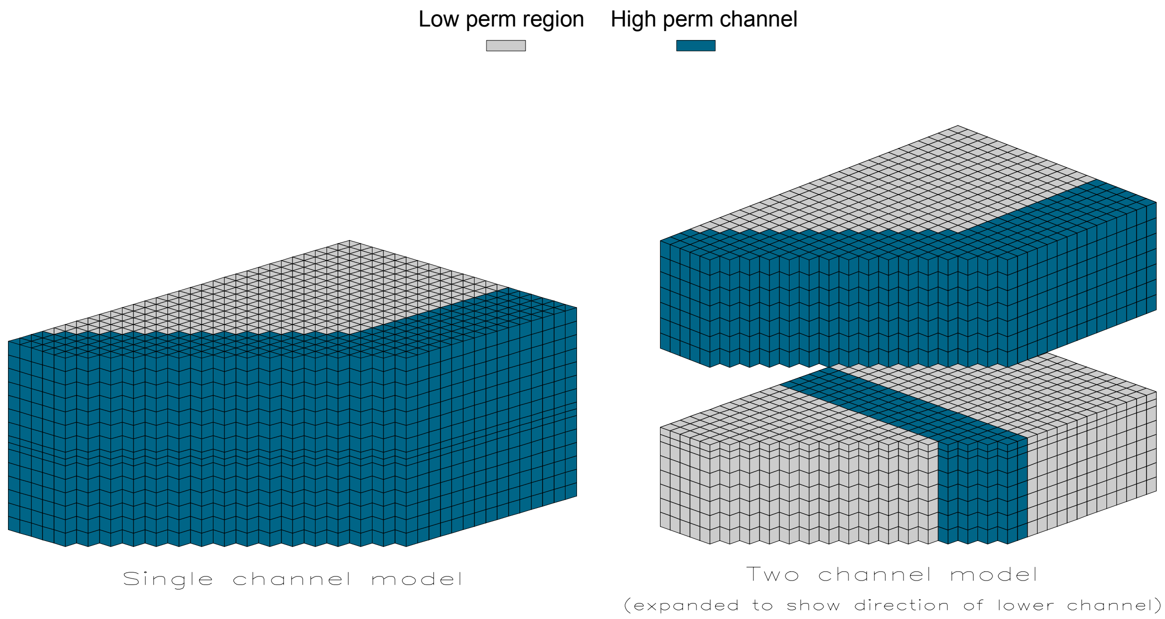

Figure 12: Schematic of channel sands models

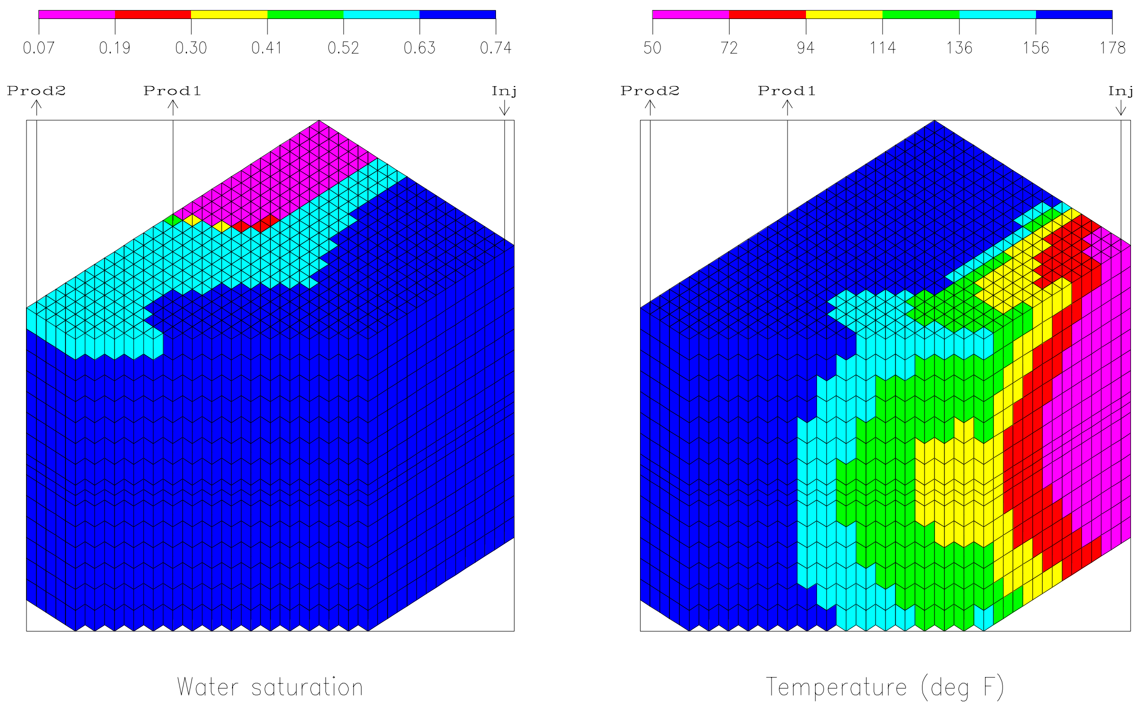

Figure 13: Water and temperature distributions at start of treatment (3000 days) in single channel model

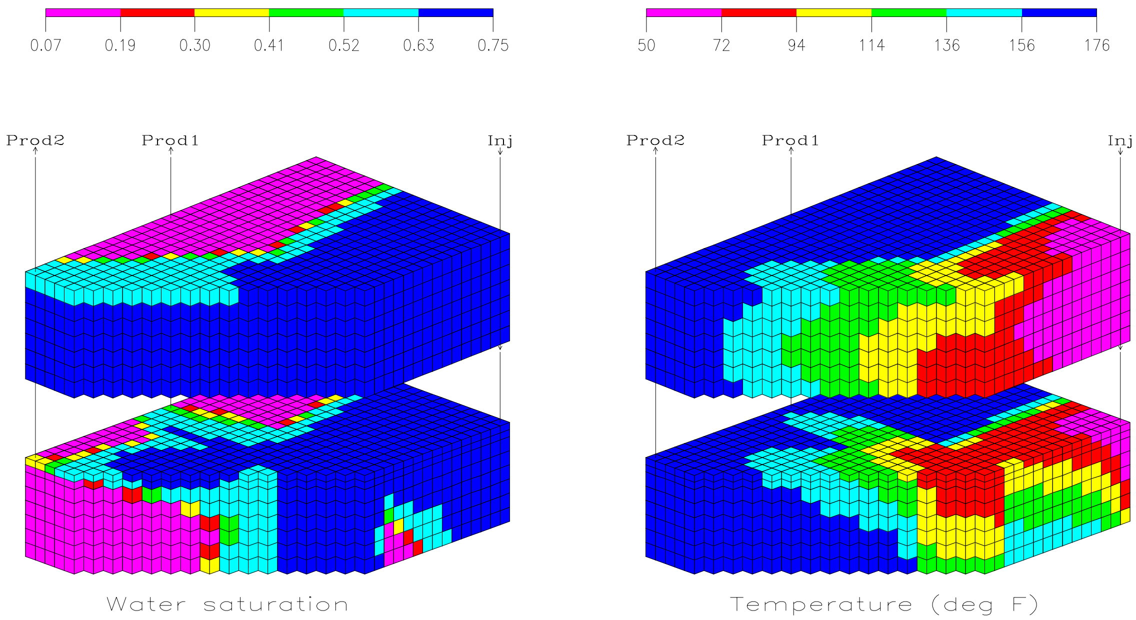

Figure 14: Water and temperature distributions at start of treatment (3000 days) in two channel model

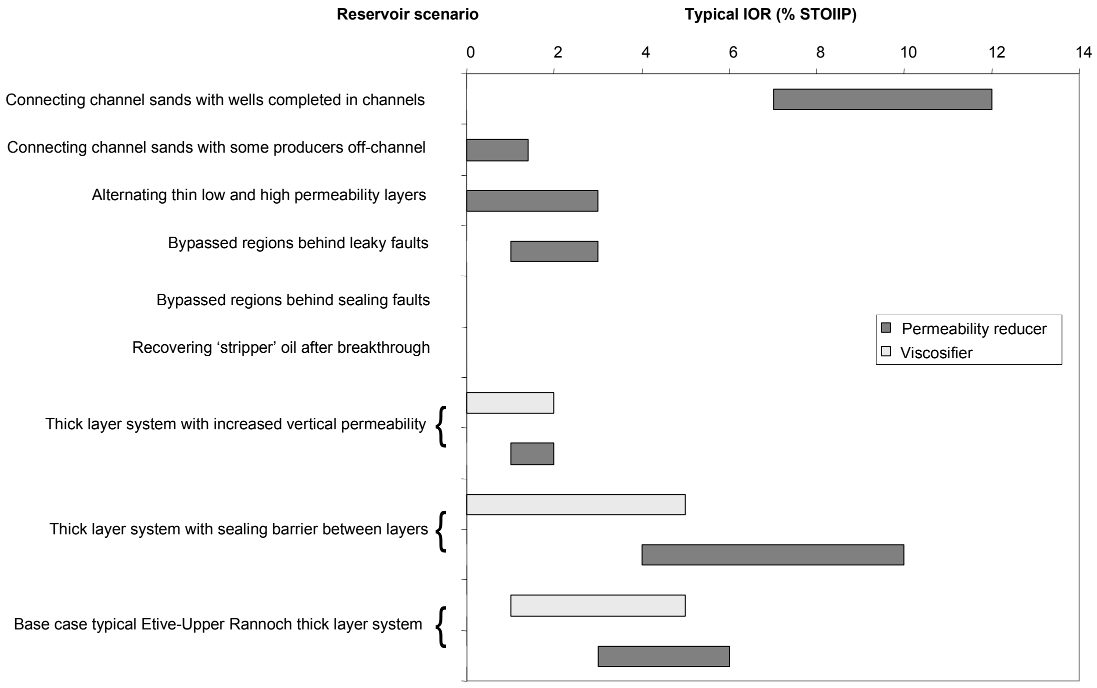

Figure 15: Summary of incremental oil recoveries for reservoir scenarios investigated